Russell D. Kane

Materials Performance Anchor Rod Questions and Responses

Author's Note: I have not been a direct party to the ongoing investigations of the Bay Bridge 150-year design or apparent problems associated with hydrogen embrittlement (HE) of high strength steel rods, corrosion of bridge components, and the use of corrosion mitigation or repair methods. At times, I have reviewed various reports and offered statements regarding the Bay Bridge rod materials, failure analysis, and environmental cracking test approaches and findings based on publicly available information, applicable industry standards, and what I feel, based on my 40-years experience of industrial and research experience with environmental cracking and HE, to be generally accepted engineering practices.

Question 1: What is the basis for estimates of the threshold stress for anchor bolt susceptibility to environmental EHE), and what is the relationship of this threshold stress to hardness?

Response: From my independent analysis of this situation, the basis for assessing threshold stress versus EHE for high strength steels of type found in the Bay Bridge rods (ASTM A554 Grade BD—with nominally C-1.0Cr-0.25Mo steel compositions) comes primarily from three sources:

- K_{EHE} vs. hardness in the published literature as represented by the Townsend paper (See Met. Trans. 1975) developed for nominal C-Cr-Mo steel compositions per UNS G41400 (C-1Cr-0.25Mo steel) using precracked specimens.
- EHE data developed by the bridge team specific to the bridge's high strength rods (defined by ASTM A354 BD similar to UNS G41400 (See Bay Bridge report dated September 30, 2014 available online)—(a) full scale rod tests and (b) precracked incremental step-loaded tests.
- Personal experience spanning 40 years related to the use of high strength steels (mostly UNS G41400-300 and UNS G43400) versus EHE for oilfield casing and tubing and offshore applications involving bolting.

Based on steels of generally similar steel composition (UNS G41400) and similar metallurgical processing (austenitizing followed by quenching and tempering), susceptibility to EHE has been shown to increase (producing a decrease in threshold stress or stress intensity for EHE) with increasing material hardness. This trend is illustrated in Figure 4 presented by Y. Chung (*MP* Nov. 2014—See Attachment I) taken from the prior work of Townsend (Met. Trans. 1975). It succinctly shows this trend in terms of threshold stress intensity for EHE (K_{IEHE}) for precracked specimens. It also shows the comparison between the K_{IEHE} for tests performed with and without Zn coating.

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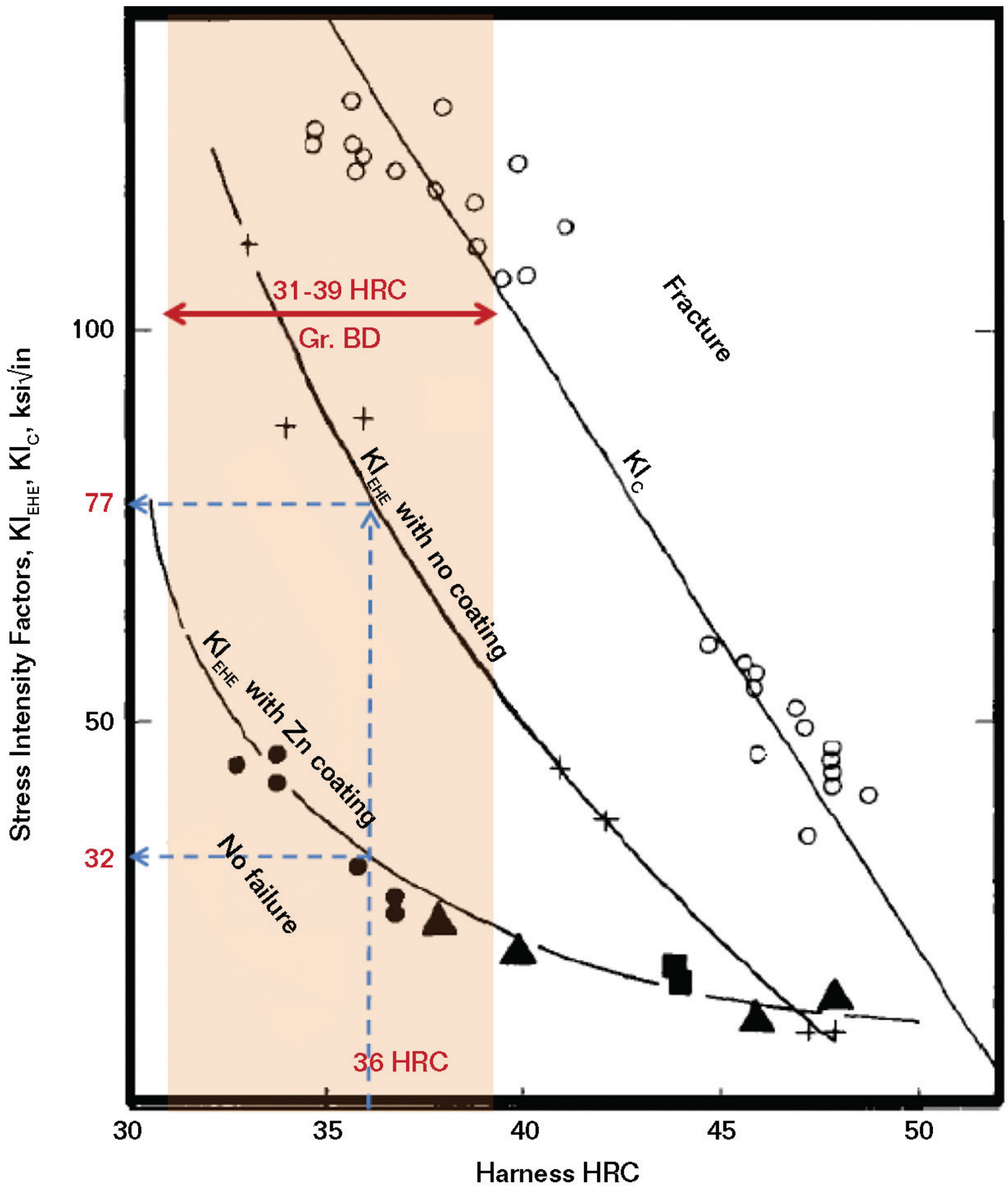
Attachment I



An important take-away from this data is that, while the threshold (stress or stress intensity) for EHE decreases with increasing hardness, the absolute value of threshold for EHE depends on the exposure condition (with Zn or without Zn). Of major importance in the matter of the Bay Bridge rods is that the values of K_{IEHE} are significantly lower for the conditions involving Zn coating on the steel versus conditions without Zn coating. This effect is caused by the increase in hydrogen charging severity on the steel surface with the Zn-coated condition.

The above-mentioned points specifically call attention to the rationale behind the ASTM A354 BD specification for the high strength steel rods that recommends against the use of Zn coatings for this grade of rods. This is the recommendation that Caltrans specifically omitted in their purchasing of the Zn-coated steel rods used in the new Bay Bridge.

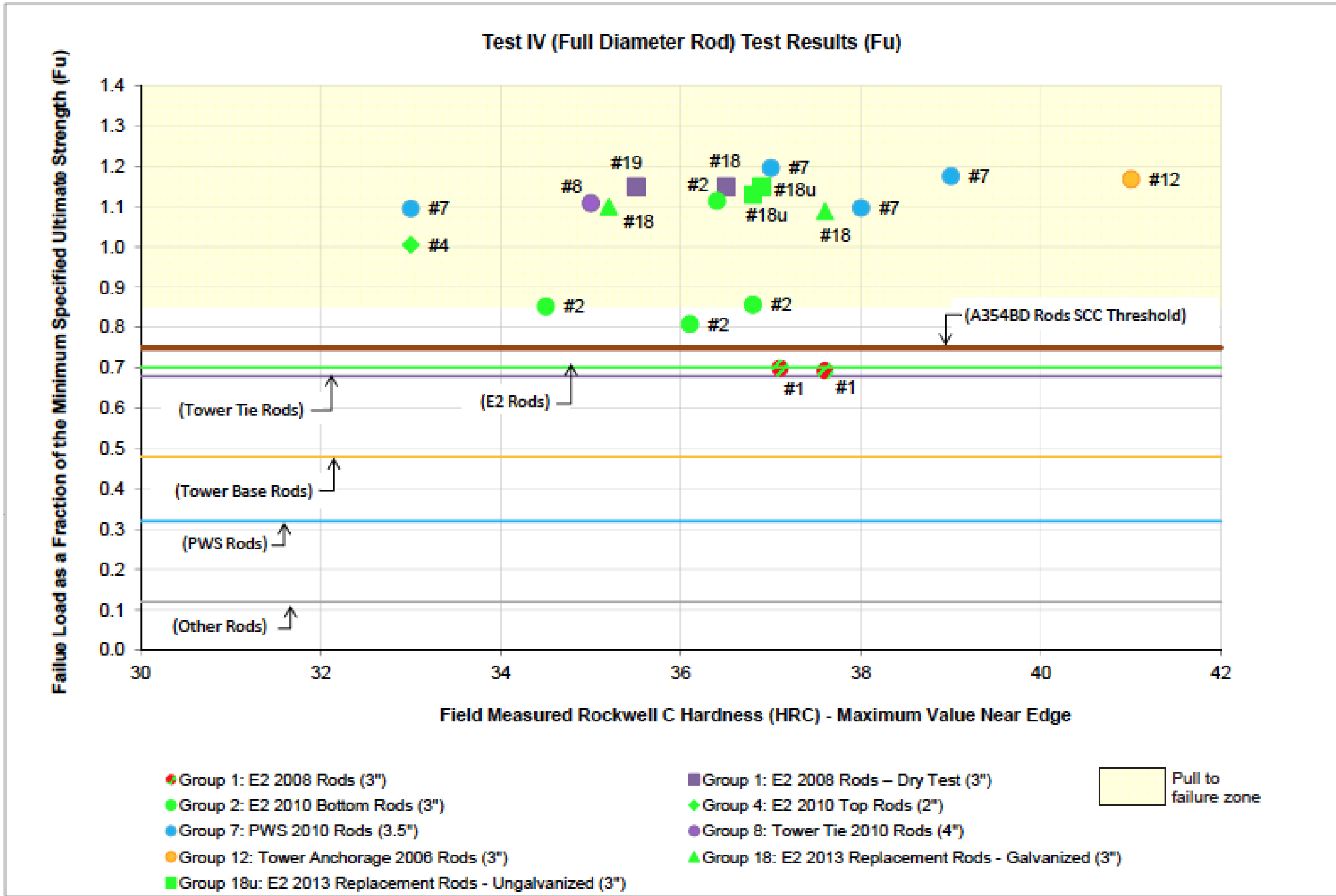
Furthermore, the Townsend data also show that over the range of acceptable hardness values for steel rods defined by the ASTM A354 DB specification – HRC 33-39 (1/4 to 2.5 in diameter rods and HRC 31-39 (rods over 2.5 in diameter) – this type of steel is expected to show a radical increase in EHE susceptibility, especially under conditions involving Zn coating. As already indicated, this point was entirely missed (or overruled) by Caltrans in the specification and procurement process for the Bay Bridge rods.

The field failures of the Zn-coated 2008 Bay Bridge rods (HRC 37-38) occurred shortly after application of a tension load at or about 0.7 Fu (70% of minimum ultimate strength). As the investigation of these failures progressed, a set of full-scale EHE tests using non-precracked ASTM A354 BD rods (3-4 in dia.) was performed in the Bay Bridge study. These rods were shown to have hardness values in the range HRC 34-37. In Phase I, EHE was observed in 3 of 4 tests performed with these rods yielding thresholds in the range 0.70 to 0.85 Fu. In subsequent phases of full-scale testing, EHE failures were not observed even with sustained loads of greater than 1.0 Fu for various test conditions, metallurgical processing conditions and at hardnesses up to HRC 41.

At the conclusion of this full-scale testing, the data showed no relationship between K_{IEHE} and hardness over the range HRC 33-41. In these full-scale rod tests, the lack of correlation between K_{IEHE} and hardness places the methodology, results, and conclusions from these tests (especially the finding that the apparent EHE threshold was 0.65 Fu) under question. There are likely several reasons for these potentially aberrant findings that include: (a) different metallurgical processing and threading methods used in some of the rods, (b) the clear likelihood, due to the large specimen cross-section, that hydrogen charging had not yet reached sufficient levels in the rod specimens, and (c) the rod specimens did not include a sharp pre-crack to overcome problems commonly associated with crack initiation in laboratory EHE tests. These data were presented in the Bay Bridge report dated September 30, 2014 (See Attachment II).

Attachment II

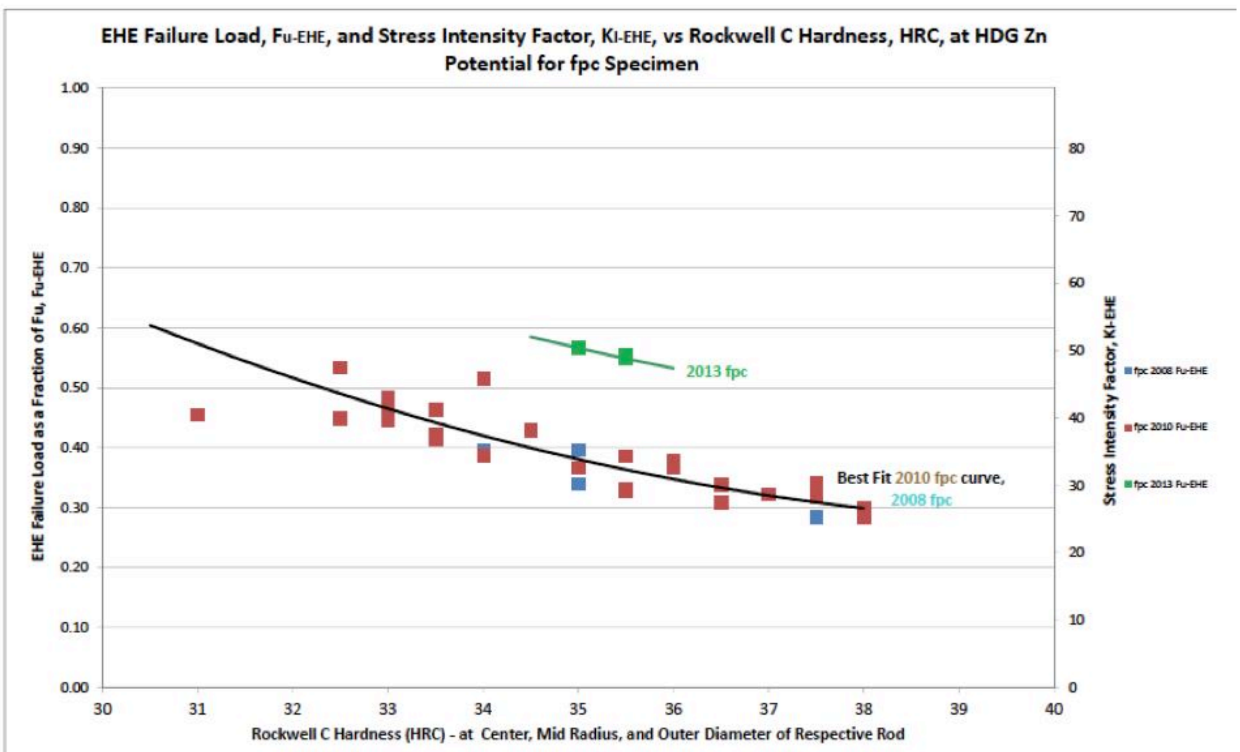
Figure 3.1-10: Test IV Failure Loads for A354BD Rods



The full-scale rod tests were followed by a series of precracked, step-loading tests (Raymond tests) on sub-size specimens cut from the high strength steel rods. These results were also presented in the Bay Bridge report dated September 30, 2014 and are highlighted in Attachment III. The data from the Raymond tests were presented both in terms of (a) threshold stress intensity (K_{IEHE}) and (b) after application of a fracture mechanics analysis to this data that represented EHE threshold as a fraction of Fu rod loading similar to that as used to represent the original field failures and the data in the full-scale rod tests.

Attachment III

Figure 3.2-11: EHE Threshold Force Ultimate and Stress Intensity



The resultant data from the Raymond tests showed a similar relationship between K_{IEHE} and hardness as found in the original Townsend study (1975). Additionally, when presented in terms of a best-fit Fu in a full-scale rod, the EHE threshold varied from 0.6Fu at HRC 31 down to 0.30 Fu for HRC 38 (the maximum allowable hardness for ASTM A354 BD rods). These data call into question the results of the full-scale rod tests performed by Caltrans.

They also suggest that, if tests were performed on steels with higher hardness levels only one or two hardness units above the allowable maximum, still lower EHE thresholds in the range 0.2-0.3 Fu may have been found. With the absence of detailed quality control records for the bridge rods, some higher hardness rods could be present. (See new article: “Fears of failure grow for rods on Bay Bridge eastern span”, October 25, 2015, http://www.sfgate.com/bayarea/article/Fears-of-failure-grow-for-rods-on-Bay-Bridge-6588743.php)

The above-mentioned range of EHE thresholds from the Raymond tests and minor extrapolation (0.2 to 0.6 Fu) is consistent with the range of loading in the Tower tie and base rods and PWS rods, which suggests a non-conservative situation exists in the Bay Bridge design with respect to failure by EHE. The results of tests conducted on 2013 rods shows significantly higher threshold for EHE than that for 2008-2010 rods. This suggests that better metallurgical processing likely resulted in a superior rod in terms of EHE resistance and that an improved rod could have been originally obtained if attention to optimized EHE resistance had been included in Caltrans' purchase specifications and followed up by adequate QA procedures.

Later in the Bay Bridge report (Figure 3.2-14), a re-analysis of the full-scale rod test data was presented as a means of (a) justifying the validity of the rod tests, (b) justifying the apparent 0.7 Fu threshold for EHE, and (c) making the questionable assertion that hardness of the steel was not a major parameter in EHE performance of the high strength steel bridge rods. Again, it must be realized that the methodology used in the rod tests still has potential shortcomings for EHE evaluation; and, as a result, serves as a non-conservative basis for assessing EHE performance of the Bay Bridge rods.

Question 2: Is there a distribution of EHE susceptibility (bell curve or other) that corresponds to the distribution of hardness values?

Response: Yes. Both the original Townsend data (1975) and the best fit line from Raymond tests in the Bay Bridge study show graphically that the susceptibility to EHE increases (K_{IEHE} values decrease) with increasing hardness within the hardness range allowable by ASTM A354 BD (HRC 31-38) and beyond. The Raymond tests show that EHE failures are predicted at much lower Fu loadings than those occurring in the original field failures and the full-scale EHE tests. They are down in the range of Fu loading to which many of the Bay Bridge rods are exposed.

An interesting comparison can be made between allowable hardness range in ASTM A354 BD (31-38 HRC) and that provide in API RP 17A (ISO 13628-1) for low-alloy steel fasteners (HRC 32 max.) that are subject to exposure to seawater under cathodic protection (similar to Zn coating). The combination of (a) the recommendation in the A354 BD specimens to avoid Zn-coating with these rods, (b) the long-established trends in the Townsend study (published in 1975) and (c) vastly lower hardness limits as defined for seawater-exposed bolting in the API standard all show that there should have been no surprise that high strength steel bolts with Zn coating would lead to a rod failure scenario in the Bay Bridge. The fact of the matter is that the question is not a matter of evaluating hardness distributions. The lack of attention to quality assurance and associated record keeping by Caltrans during the manufacturing and procurement of the rods, does not allow for a complete analysis of hardness distributions in the complete set of bridge rods at this time for such an exercise to be meaningful.

Question 3: What is the safety factor for the hardest anchor bolts?

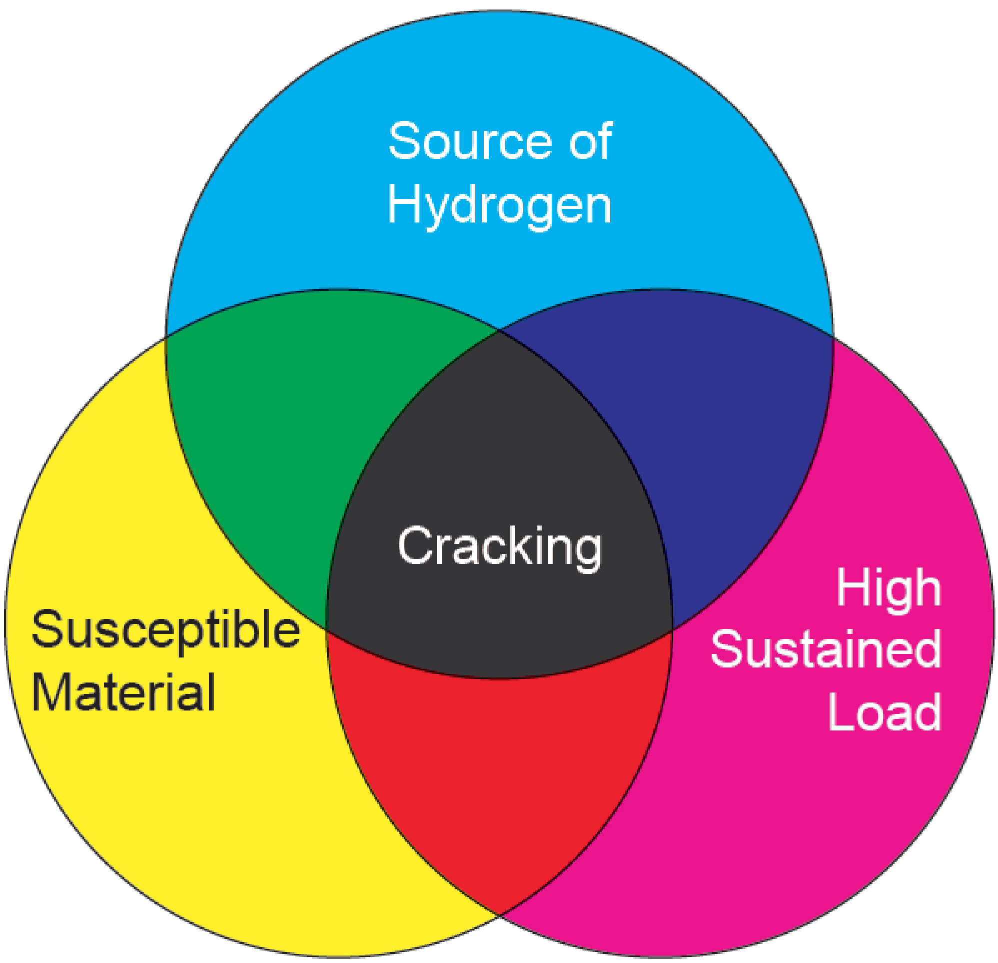
Response: If you believe that the original Townsend data (1975) and the data from the Raymond tests in the Bay Bridge study are credible (which I do) AND believe that there are potential methodology issues with the full-scale rod EHE test (which I do), there is little or no safety factor for the hardest rods per the ASTM A354 BD specification or the highest loaded rods, particularly when put into service with Zn coating. The range of Fu loadings in many of the Bay Bridge rods are precisely in the EHE threshold range (0.2 to 0.6 Fu) and too close for comfort when recommending a 150-year design life for the bridge. Y. Chung has looked at test scatter and its impact on apparent safety factors on the bridge rods. I will leave that topic to him to address.

Question 4: Did the additional stresses applied during attempts to achieve tower verticality meet or exceed that safety factor?

Response: This is a very likely scenario. As shown in Attachment IV (Figure 1.3-8 from the Bay Bridge Report), the main three variables in EHE are: (a) adequate source of hydrogen, in this case from corrosion of the Zn coating, (b) sufficient tensile stresses, and (c) adequate material susceptibility to EHE. A fourth variable often omitted in this analysis is the parameter of time, as in the time needed for to reach a critical level of internal hydrogen over a critical volume of material inside the steel, and the time to initiate an EHE crack prior to the onset of fast fracture by EHE. This is precisely why the results of the previous Townsend work and the current Raymond work should be weighed more heavily than the full-scale rod tests. By their inherent small cross-section and pre-crack design, they overcome the barriers to EHE initiation and the vagaries of installation and actual in-service variables.

Attachment IV

Figure 1.3-8: Conditions for Hydrogen Embrittlement Cracking



In terms of application of stress in an engineering structure, a basic tenet of engineering design is that all stresses present in a component are additive and include sources from the structural in-service design, installation (and misalignment), and those that are internal to the component (residual from the manufacturing process). If the rods were exposed to higher total tension stresses as a result of achieving tower verticality, then that would tend to reduce the safety factor (if in fact, there was a safety factor) and would result in increased susceptibility to EHE of the steel rod with Zn coating when exposed to moist conditions.

Question 5: Is it critical for bolt galvanizing to remain intact for long-term corrosion protection, and is it reasonable to expect galvanizing to remain intact for the 150-year design life?

Response: Zn coatings do have a finite life that varies depending on the severity of the service environment that generally increases with the amount of moisture, salt and other contaminants, service temperature, and scenarios involving damaged coatings and wet-dry conditions. The harsh reality is: with the range of hardnesses in these bolts (even if HRC 38 is taken as a maximum value), EHE can still be a problem in some applications even without Zn-coating. It would be a good engineering decision on the Bay Bridge project to determine the maximum possible service life of Zn coatings under various service conditions and also address the impact of steel corrosion once the Zn coating has been exhausted.

Question 6: Is it possible to apply proper maintenance measures (grout, grease, paint) for anchor bolts that are submerged in water intrusions from the bay?

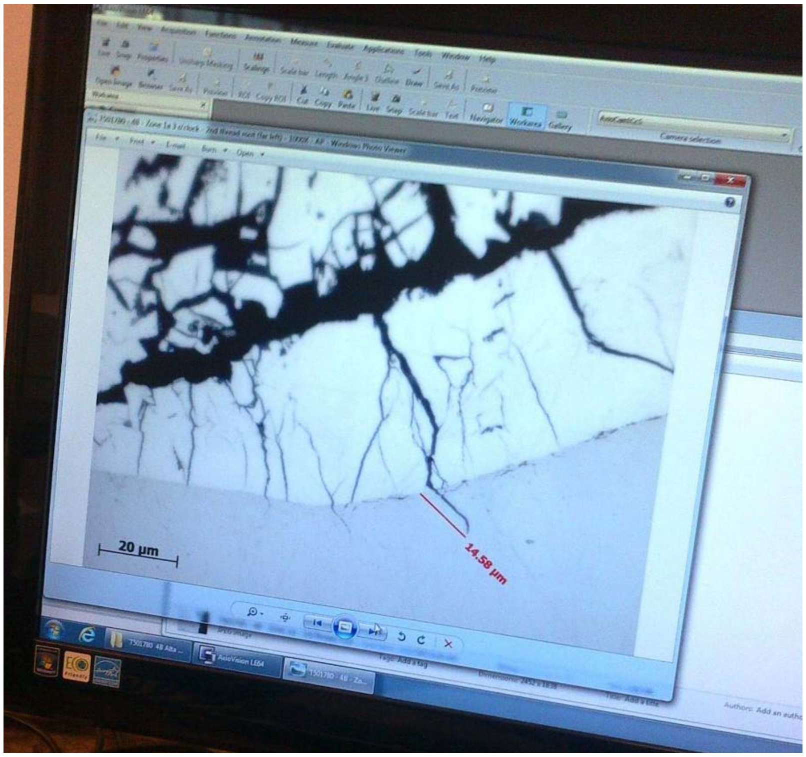
Response: The answer to this question comes from both personal experiences with bathtub caulk, plumbing, driveway or foundation repairs, and from complex industrial systems and even the first space shuttle disaster. Sealing and/or dehydration systems are hard to implement in dynamic structures in locations that are remote or not easily prepared or later inspected, and particularly when implemented as a retrofit where residual moisture is hard to remove.

In this case, the bridge has shown to have many sources of moisture already present: internal condensation, windblown moisture (and salt spray), and seawater intrusion. The tasks of moisture removal (macro-dehydration), drying of the internals of the structure and crevices, removal of salt water ingress and resultant salt contamination, hydroscopic salt residue, sealing, barrier to or displacement of future internal moisture, and proactive future monitoring and remedial actions are daunting tasks that all come with the need for major long-term attention, monitoring and funding. My answer is no. It would be naïve to think that long-term corrosion protection can be implemented at this point or in the future.

Question 7: What is the significance of the microcracks that were discovered in all of the recently-examined bolts?

Response: As described in a recent newspaper article titled “Ominous new cracks found on Bay Bridge rods” (on sfgate.com dated June 24, 2015, a Caltrans representative indicated that microscopic cracks were found on at least two more Bay Bridge rods exposed to water. A third rod reportedly showed evidence of “fast fracture.” Apparently, there was also evidence of cross-threading and galling during the installation of the rods that adds another issue on top of that imposed by EHE. Cross-threading further adds to the intensity of local (and difficult to quantify) stresses in the threads, a region of the rod that already has stress concentrations from the thread profile and that has been shown to be a preferred site for EHE.

The new observations of micro-cracks (more evidence with photos in recent Exova studies – See new Figure below) and fast (likely EHE) fracture suggest that Caltrans' understanding of EHE problem with the Bay Bridge rods is still in a state of flux. While trying to convince itself and the public that the Bay Bridge rods are safe and explain away the apparent inconsistency between the results of their full-scale and small-scale (precracked) tests, these new rod cracking incidents indicate that: (a) EHE is an ongoing problem with the Bay Bridge rods, (b) current rod load levels are in the range where EHE can occur (possibly below apparent EHE threshold levels), and (c) rod replacement or some form of massive corrosion remediation is necessary to achieve a true 150-year design life for the new bridge.



The problem with corrosion remediation through dewatering and use of greases and caulking are that the bridge structure is already wet and apparently seeing saltwater influx. Use of these remediation methods in a retrofit-mode under these conditions will make it hard for Caltrans to assure success, particularly over the long design life of the bridge. A possible non-corrosion remediation would be to lower the loading on the rods; however, the question is how low the stress intensity must be reduced to achieve a EHE-free bridge while allowing the rods to perform their intended function. The two sets of Caltrans data tell different stories. If this approach is taken, then the more conservative (lower EHE threshold) results should be used. The ultimate cure for the rod failure issue is replacement with new rods, without Zn coating and likely made with controls placed on metallurgical processing and hardness limits to assure resistance to EHE.

Question 8: Are there any long-term corrosion concerns that are not related to hydrogen?

Response: There are several potential corrosion and non-corrosion issues that I've gleaned that include: flawed welds, misaligned deck sections, box sections with water in them, botched grouting and sealing of existing elements of the bridge. I have not done an exhaustive study and do not have a complete list. I'd suggest contacting Caltrans or other the bridge specialists with corrosion background for this list.

Question 9: An article in the June *MP* postulated a failure mechanism involving exposure of the rods to high pH water in the top hats during the interval between grouting and pre-tensioning. Are there any comments on that possibility?

Response: Steels with hardness values in excess of HRC 30 can be susceptible to many forms of environmental cracking. This is why it is necessary in the design stage of a project (particularly where high strength materials are involved) to obtain critical input from metallurgical/corrosion specialists with expertise in environmental cracking. Additionally, it is important to incorporate their recommendations and have performed critical tests in advance of purchase so that manufacturing specifications can be developed that assure a cracking-resistant design. In the case of the existing A354 BD rods, there was a complete lack of consideration for environmental cracking (and EHE specifically) and a lack of knowledge of the impact of material hardness and Zn-coating on the serviceability of these rods.

From my experience in the oil and gas industry, I have observed high pH cracking of high strength steels. This form of attack is typically called stress corrosion cracking and more specifically, in some cases, caustic cracking. In the cases I have seen, it was found in steels with HRC >30, elevated temperatures (150 to 350 °F) and requires the steel and environment to produce a particular range of electrochemical potential where the SCC mechanism can operate. The caustic cracking mechanism can also be made worse by service conditions that concentrate the high pH solution, as would especially be the case for evaporative or repeated wet-dry conditions. My suggestion is, if such conditions exist, environmental cracking in high pH water needs to be seriously considered as a failure mechanism until it has been given an in-depth technical review.